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MARS NETWORK CONSTELLATION DESIGN DRIVERS AND STRATEGIES

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NASA's Jet Propulsion Laboratory has initiated the design of a spacecraft constellation that will provide communication relay and navigation support for a variety of future Mars missions. The objective of this constellation is to provide increased data return, enable autonomous onboard navigation with reduced reliance upon Earth-based tracking data, and substantially lower the combined operations costs of anticipated missions for Mars explorations. This study presents the results of the system analysis and trade studies performed on different constellation designs. Anticipated user requirements, candidate Mars scenarios, and the desire to supply an evolving, enabling navigation/communication infrastructure for future envisioned missions have guided the constellation selection process. Navigation and communication requirements, drivers, and metrics are presented and discussed. A preliminary design is examined in detail. It is a low altitude, retrograde hybrid constellation consisting of two subconstellations. The first subconstellation provides focused coverage near the equator, and the second is at a higher inclination and provides global coverage within a finite span of time.

INTRODUCTION

Within NASA's vision to better understand "our cosmic origins and destiny, and how these are linked by the cycles of evolution," NASA has made the commitment to explore Mars. Recent successes towards fulfilling this vision include the Mars Pathfinder and Mars Global Surveyor programs. The science data returned from these missions has been priceless in increasing our understanding of Mars. Current and planned missions to Mars include the Mars Climate Orbiter, the Mars Polar Lander, and the Mars Sample Return missions. These missions will continue well into the next millenium with a plan to launch a series of orbiters and landers every 26 months as Mars and Earth move into proper alignment. One of the goals sought is to eventually establish a manned presence upon the martian surface.

The increased number of martian orbiters and landers poses the problem of satisfying an increased demand for navigation and communication services. A very viable solution that meets this demand is the implementation of a martian satellite constellation of micro-satellites with the task of providing navigation and communication services to the Mars in-situ users. This constellation would extend the existing capabilities of NASA's Deep Space Network (DSN). Also, the additional infrastructure provided by the constellation would be an enabling technology that future missions could take advantage of in their baseline planning. It is the objective of this research to address the design, development, and implementation of a satellite constellation that would have the following purposes:

1. Serve as relay between Earth and Mars to send required commands to ongoing missions.
2. Serve as a platform for position determination, in as near real time as possible, of orbiting satellites and surface landers/rovers both with respect to Mars and to each other.
3. Serve as relay between Earth and Mars to receive the data generated by the ongoing missions.
4. Serve as a cross-communicating relay between the in-situ mission elements.

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Table 1: Performance Goals for Designing the Mars Network Constellation

1	Provide global coverage over a selected time span. Some mission types, such as seismic or meteorological networks, require global low volume communication support. The practical result is to deploy spacecraft in inclined orbits that have coverage to the poles.
2	Provide large volume communication support of the equatorial regions. The bulk of the currently identified martian surface users will be located around the equator. Additionally, the first human missions are planning near equatorial landing sites. The practical result is to deploy a portion of the network in near equatorial orbits.
3	Maximize communication and navigation performance across all latitudes and longitudes.
4	Minimize communication and navigation performance variations across all latitudes and longitudes, with the exception of ensuring higher capacity communications support at the low latitudes.
5	Provide maximum utility during buildup of the constellation
6	Provide redundant coverage in the event of the loss of any single spacecraft. A loss results in a constellation configuration that suffers degraded performance, however, one that can still fundamentally accomplish goals 1 and 2: provide focused equatorial coverage and global coverage in time.
7	Minimize coverage variability due to long-term orbit perturbations. In particular, minimize orbital precession effects on the coverage geometry. Minimize orbital maintenance as measured in operations time/cost and expended Delta V

In determining a design for this constellation, the potential field of martian users that will be present during the next decade is used to determine the amount of coverage and robustness required by the constellation. The research seeks to maximize the amount of coverage while minimizing the number of satellites needed, taking into account the desired constellation robustness. The robustness of the constellation reflects how much coverage can be maintained with the loss of one or several satellites within the constellation. The constellation's communication and navigation performance is investigated via the use of selected metrics. These metrics reveal the design trades that must be made in order to field a constellation that satisfactorily meets the communication and navigation needs of the user community. The study also addresses the performance of partial constellations as the Network capability is built up over time.

A companion paper, entitled "Architectural Design for a Mars Communications & Navigation Orbital Infrastructure," Ref. [1] provides an overview of the Mars Network and its anticipated capabilities.

MISSION REQUIREMENTS AND DESIGN GOALS

Selecting a baseline constellation design for the Mars Network begins with consideration of the user's requirements for both locating a given asset and communicating with it. These requirements are prime drivers for developing the Network's needed functional capabilities. Some anticipated early users of the Mars Network include the 2003 & 2005 Mars Sample Return (MSR) missions. Each MSR mission includes a lander, a rover, and an orbiting canister that require communications and navigation services. Other anticipated users include the Micromission Aircraft, the Beagle 2 lander, and the Netlanders. Most of the landed assets for these missions are expected to be between ±15° in latitude. Details regarding these missions can be found in the companion paper.[1] With these users in mind, the performance goals listed in Table 1 have been identified as having a primary influence on the constellation design of the Mars Network.

Since the constellation serves the user's communications and navigation needs *simultaneously*, design trades between these functions must be considered in orbit selection. As is often the case with multi-objective design problems, these objectives compete with each other, and a challenge is found in creating a common platform that maximizes the performance of both functions. Specific geometry factors affecting communication performance include coverage characteristics and slant range between the user and an in-view satellite. For instance, the received data rate varies as an inverse square function of slant range between the transmitter and receiver, and data volume depends on the pass length times the received data rate. Because the surface users typically operate at low power, in order to maximize communication performance, it is desirable to have an orbital geometry where range is minimized and pass length is maximized. For navigation purposes, there are additional geometry considerations, in addition to pass length and slant range, that must be considered in order to obtain an accurate navigation solution. Ideally, near real time position determination requires several satellites to be simultaneously in view of a user asset. For instance, to unambiguously estimate in real time three position coordinates and a time offset using a range observable requires four in-view satellites (4-fold coverage). Obtaining this type of geometry with a constellation with a small number of satellites requires a high orbital altitude. Since the Mars Network constellation is currently limited to a maximum size of 6 satellites, and low altitudes are desirable for communications, 4-fold coverage cannot be achieved using a typical Walker constellation or a Streets of Coverage constellation.[2,3] The best that can be achieved is position determination over a minimized time period using filtered data. Clearly, selection of an orbital altitude plays a central role in fulfilling both the communications and navigation mission. It is the interplay between altitude and the other geometry considerations that forms the basis of the ensuing analysis.

PRELIMINARY COVERAGE ANALYSIS

As the previous discussion indicated, a factor common to both communication and navigation performance is selection of desirable coverage properties (such as maximizing total pass length and minimizing the maximum time between satellite revisits). The low altitude requirement of the communication mission, coupled with a small constellation size, prevents selection of an orbital configuration that yields continuous global coverage. However, it is possible to select a constellation that is sufficiently low in altitude, and can cover the planetary surface within a selected *period of time.* Furthermore, Performance Goal 2 dictates that coverage should be focused at the equator. To achieve these ends, hybrid constellations with different inclinations are considered. A clear advantage of multiple inclinations is that each orbit plane yields coverage in a region between maximum/minimum latitude excursions of a satellite's coverage circle. Thus the use of multiple planes allows the designer to spread support evenly over latitudinal regions.

Consider the relationship between the satellite altitude h and the radius of the central angle 6 associated with the satellite's coverage circle,

$$\cos(\theta+\beta)=\frac{R_m}{R_m+h}\cos\beta=\frac{R_m\cos\beta}{a(1-e^2)}(1+e\cos f)\,, \tag{1}$$

where f is the true anomaly of the satellite in its orbit, R_m is the mean radius of Mars, and β is the minimum elevation angle that a surface terminal can have for the satellite to be in view. It has been set to a nominal 15° for this study. The other elements in Eq. (1) are semi-major axis a and eccentricity e. Figure 1 illustrates the geometry associated with Eq. (1). Clearly, as the satellite altitude h increases the radius of the central angle 6 increases. Furthermore, as the satellite moves in its orbit it maps out a swath over the inertially fixed celestial sphere. The swath closes on itself in one orbital period. Careful examination of a swath from Figure 1 indicates that the width $2\Delta\alpha$ of a swath along a line of constant declination δ_c reaches a maximum as the satellite nears its highest excursion in declination. (Note: declination on an inertially fixed celestial sphere is equivalent to latitude on a rotating spherical Mars.) Hence, maximal regional coverage occurs for circular orbits in the neighborhood of the maximal/minimal latitudinal excursions. With this in mind, it is reasonable to conclude that a constellation design consisting of multiple inclinations has the potential for a more uniform coverage distribution over latitude than a constellation with fewer inclinations.

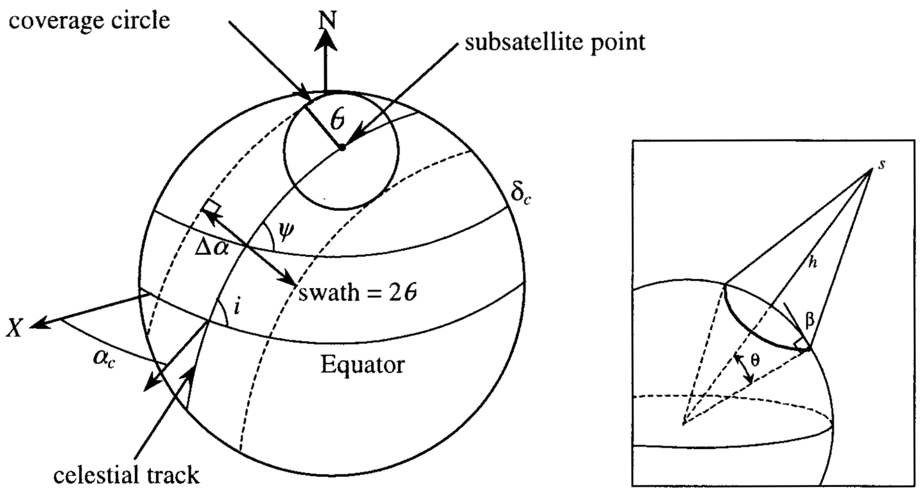


Figure 1: Coverage geometry

Most orbital planes experience drifts in orientation due to the presence of secular effects from the planet's oblateness. Of primary interest for placement of circular orbits is the first order secular drift rate for the ascending node, this takes the form,

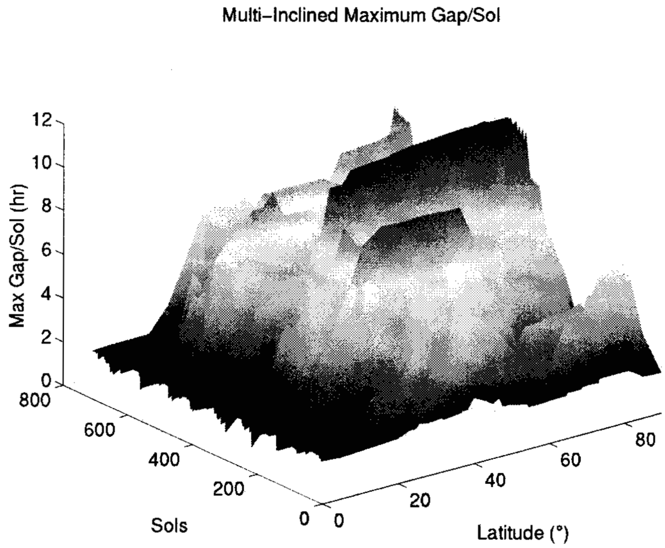
$$\dot{\Omega}_{\text{sec}} = -\frac{3nJ_2}{2(1-e^2)^2}\left(\frac{R_m}{a}\right)^2 \cos i, \tag{2}$$

where n is the satellite mean motion, i is the orbital inclination, and J_2 is the oblateness coefficient. The functional dependence on inclination implies that orbit planes at different inclinations drift at separate rates. Thus, a constellation configuration selected with an initial phasing between ascending nodes that yields a desirable coverage characteristic (i.e., minimal maximum gap time between revisits to a landed element station) will, in time, drift away from that desired characteristic if the inclinations are selected poorly.

The elements for the primary candidate constellations considered in this study are identified in Table 2.

Table 2: Primary candidate constellations considered for the Mars Network

SatID	***Multi-Inclined*** (h,i,Ω,M) (km,deg,deg,deg)	***4inc65*** (h,i,Ω,M) (km,deg,deg,deg)	***4retro111*** (h,i,Ω,M) (km,deg,deg,deg)	***4inc80*** (h,i,Ω,M) (km,deg,deg,deg)
1	(800,10, 0,0)	(1100,10, 0, 0)	(800,172, 0, 0)	(1100,10, 0,0)
2	(800,35, 60,0)	(1100,10,180, 0)	(800,172,180, 0)	(1100,10,180,0)
3	(400,55,120,0)	(1100,65, 0, 0)	(800,111, 0, 0)	(400,80, 60,0)
4	(400,65,180,0)	(1100,65, 90, 90)	(800,111, 90, 90)	(400,80,120,0)
5	(400,75,240,0)	(1100,65,180,180)	(800,111,180,180)	(400,80,240,0)
6	(400,85,300,0)	(1100,65,270,270)	(800,111,270,270)	(400,80,300,0)



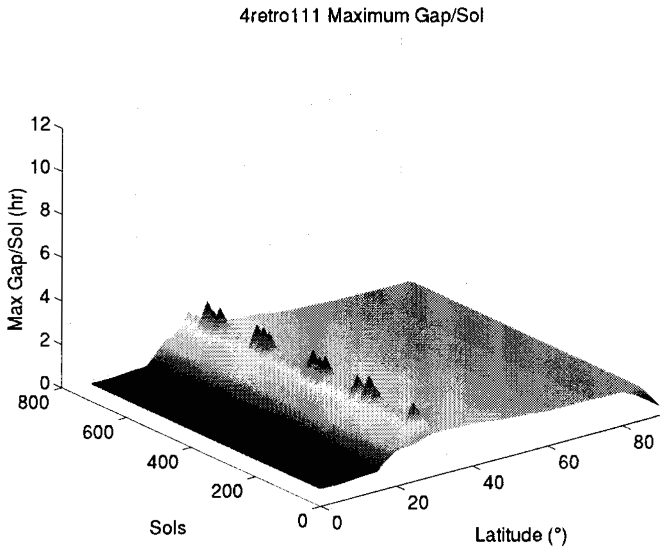


Figure 2: Maximum gap time per day statistics for the Multi-Inclined and 4retro111 constellations

To assess the possibility of poor geometry resulting from relative nodal drift, two of the candidate constellation configurations are examined in detail, Multi-Inclined and 4retro111. The constellations are propagated for a two year period with inverse square and secular oblateness effects active during the propagation. At 5° intervals in latitude is a landed element that samples every 3 minutes whether a satellite of the constellation is in view. A useful statistic to formulate is the maximum gap time between revisits of any member of the constellation to a given landed element. This value is assessed every martian sidereal day (called a Sol), and, thus, is called "Maximum Gap/Sol." Figure 2 illustrates this statistic for the constellations Multi-Inclined and 4retro111.

Examination of the Multi-Inclined results reveals a region beginning around ~ 300 days and lasting to ~ 400 days where the Maximum Gap/Sol > 8 hrs for the latitudes from 35° to 80°. The largest value of the statistic found is 11.6 hrs. As will be shown, in its starting configuration the Multi-Inclined constellation has superior communications performance as compared to the other constellations, however, after a year

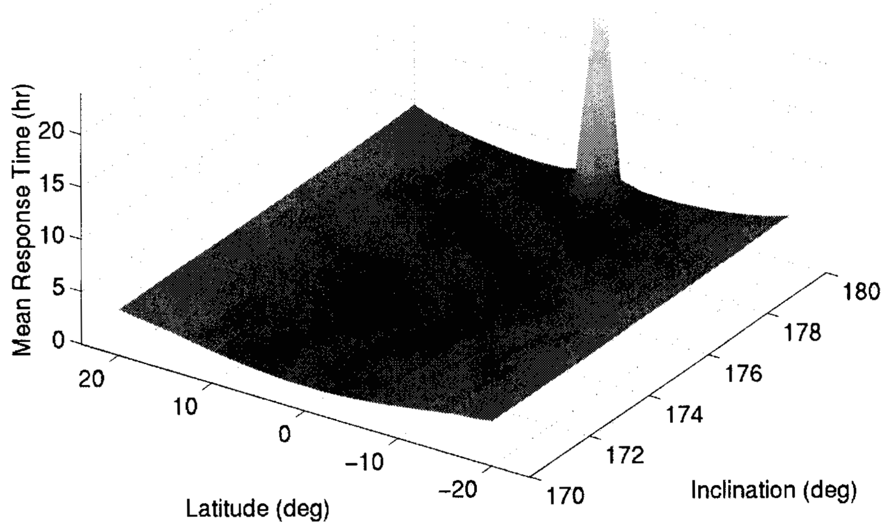


Figure 3: Average time a surface user (as a function of latitude) takes to determine position with 10 m uncertainity via collection of 2-Way Doppler data to a satellite (as a function of inclination and at 800 km altitude).

the geometry has degenerated to yield this unacceptable gap statistic. Using a smaller number of plane inclinations can rectify the situation. The 4retro111 constellation has two subconstellations: the first is near equatorial with 2 planes spaced 180° apart in ascending node and each at 172° inclination; the second has 4 planes spaced equally in ascending node and each at 111° inclination. Each subconstellation exhibits a rigid rotation of its individual orbit planes. As a result, the phasing between planes within a subconstellation, to first order, remains fixed. Note that second order perturbations can introduce long periodic phasing effects that might need to be controlled, this is an area of future investigation. As can be seen in Figure 2, the practical implication of the fixed nodal phasings is that the Maximum Gap/Sol statistic is relatively independent of time. Furthermore, for the 4retro111 constellation, the gap time has been reduced to a global worst case of 234 min at 25° latitude. Note that the average maximum gap time at this latitude is 126 min, which implies the global worst case performance does not persist for very long. These worst case values represent a poor phasing scenario between passing spacecraft and a user at 25°. Specifically, the user just misses an overhead satellite, rotates in an orbital period longitudinally out of the return path of that same satellite, and then has to wait for the neighboring satellite to come in view. Fortunately, as reflected in the average at this latitude, these occasions are infrequent. Also, not unexpectedly, the 25° latitude represents the region where the two subconstellations interface. The best case performance occurs in the near equatorial regions below 25° latitude with the best case being 48 min at 0° and 5° latitude. It will be shown that the superior pass statistics associated with the 4retro111 constellation contribute to good communications and navigation performance.

The geometry of a satellite pass over a user's terminal is an additional coverage property that must be considered when selecting the constellation orbit plane inclinations. If all the orbiters are polar, most passes over a surface site will be predominately south to north or north to south. This makes it difficult to reduce position uncertainty in the east-west direction. Similarly, if the passes over a location are east to west or west to east, as with near equatorial satellites and surface terminals, it becomes difficult to reduce north-south position uncertainty. Navigation is best served by having a variety of pass geometries. This suggests the use of orbit inclinations inclined sufficiently far away from pure polar or pure equatorial. For

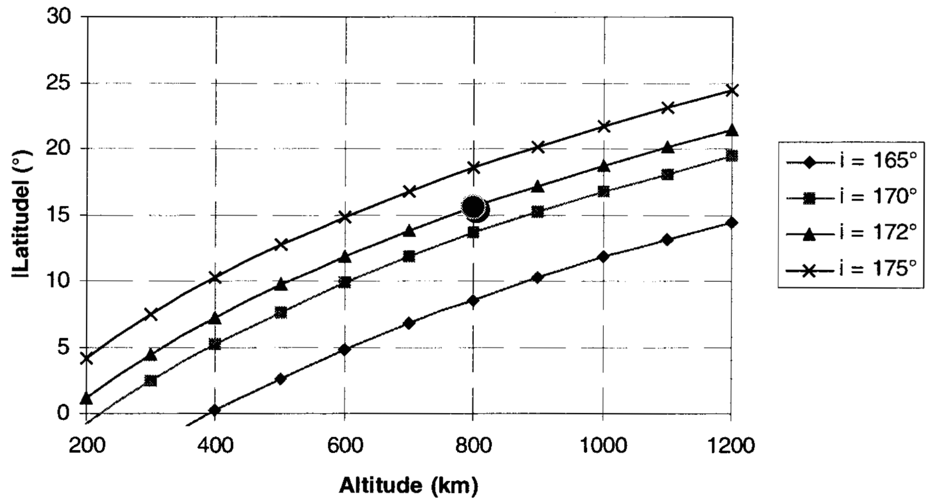


Figure 4: Maximum absolute latitude visible on every pass from a single low-inclination satellite

the hybrid constellations considered in this study, near equatorial positioning performance is a significant consideration. Figure 3 shows the average time a surface user at various near equatorial latitudes takes to determine its position to within 10 m by collecting 2-Way Doppler data to a single satellite. The satellite is in a circular orbit at 800 km altitude, and at inclinations between (170°, 180°). (Note: Details associated with computing the Mean Response Time are forthcoming in a later section). The figure illustrates that for satellite inclinations below 178°, a surface user between +/- 5° latitude experiences an extreme sensitivity to the time needed to get 10 m positioning accuracy (see the spike that jumps from ~ 2.4 hrs to a saturated value of 24 hrs – theoretically the value is unbounded). To avoid this sensitivity the selected inclinations range between (6°, 174°). These limits provide sufficient margin to minimize the potential for other, unaccounted for factors (i.e., additional error sources such as atmosphere delays) that might magnify this positioning sensitivity.

Given that the first satellite will provide support only to the near equatorial regions, it is desirable to know the maximum latitude $L_{\max}$ *(north and south)* that a surface user can view the satellite, on every pass, as a function of altitude and inclination. In the single satellite case the computation for $L_{\max}$ is simple, and is found using,

$$L_{\max} = \begin{cases} \max\{0, \theta - i\}, & i \le \dfrac{\pi}{2}, \\ \max\{0, \theta - (\pi - i)\}, & i \ge \dfrac{\pi}{2}. \end{cases} \tag{3}$$

The results for several near equatorial *retrograde* inclinations are shown in Figure 4. The analysis assumes a 15° minimum elevation angle. As expected, the more equatorial inclinations and higher altitudes result in consistent coverage to the widest latitude band. The current best design point corresponding to 4retro111 (shown as the large dot) is at an altitude of 800 km and inclination of 172°, and yields a pass on every orbit to users within +/- 15.6° of the equator.

Pass geometries typically vary with time and can exhibit a variety of behaviors ranging from periodic to quasiperiodic. If the satellite orbit mean motion is commensurate with the martian mean rotation rate, then the associated pass geometry will exhibit periodicities. The practical implication of this behavior is communication and navigation performance will exhibit a longitudinal dependence that is stationary in time. To avoid these potential long term longitudinal nonuniformities, the orbit altitudes considered in this study are selected specifically to *not* yield commensurate mean rates. Mathematically the pass geometry will be quasiperiodic and never repeat, thus preventing long term longitudinal biases from forming.

As a final observation regarding coverage properties, consider coverage near the poles. Recall that the maximum latitudinal (North or South) excursion of a satellite's celestial track (or, equivalently groundtrack) in an inclined orbit is equal to its inclination. Thus for a satellite coverage area to include the poles the following constraint must be satisfied,

$$\begin{aligned} &\theta + i \geq \frac{\pi}{2}, \quad && i \leq \frac{\pi}{2}, \\ &\theta + \pi - i \geq \frac{\pi}{2}, \quad && i \geq \frac{\pi}{2}. \end{aligned} \tag{4}$$

Clearly, a minimal condition for polar coverage is obtained by setting Eq. (4) to equality. This equation serves as a guide towards selecting inclination and altitude for the upper subconstellation.

From the preceding analysis it can be concluded that a hybrid constellation with only two subconstellations, the lower inclined planes for equatorial coverage and the higher inclined planes for mid-latitude and polar coverage, yields a geometry that is relatively stable in time and produces favorable pass statistics. Utilization of this hybrid scheme satisfies Performance Goal 7 to first order. Analysis of 2nd order perturbation effects and their impact on meeting this goal is a current area of study.

COMMUNICATION AND NAVIGATION METRICS

Designing a constellation with desirable coverage properties is a first step towards orbit selection, however, the primary focus in selecting the Mars Network constellation is maximizing return of science data, and minimizing the time it takes to compute a user's position to a specified accuracy. With this in mind, the following communication and navigation metrics have been selected to measure the performance of the candidate constellations:

1. Mean Data Volume/Sol/Watt – Data quantity metric for a power limited mission. Power limited missions are those that incorporate solar cells and batteries allowing them extended lifetimes and daily operations limited by the power producing capabilities of the solar cells, e.g. rover with solar cells. Analysis shows that lower altitudes, 400-1200 km produce the highest total data return per sol. While higher altitude spacecraft produce longer passes that partly compensate for the longer slant ranges, it is the range-squared energy dispersion losses that dominate. Therefore, the lower altitude spacecraft produce more total data return.
2. Mean Response Time (MRT) – Average time to collect sufficient measurement observations to compute a users position to a prescribed accuracy. Any constellation satellite that passes over a landed element collects measurement information to that element. When the constellation has collected sufficient observations to compute the position of the user to a specified accuracy, the time taken to collect this data is recorded. This time is a function of pass geometry and element location. It varies as the constellation is propagated forward in time. Minimizing the time that it takes to collect these observations is a key concern for enabling autonomous rover operations.

An additional communication metric that has been considered while analyzing the various constellation geometries is the Mean Data Return/Joule – a data quantity metric for energy limited missions. Energy limited missions are those that arrive with a fixed energy supply (i.e., the DS- 2 surface penetrator), and have no means of recharging this supply. When the battery is depleted, the mission is over. Since energy is dispersed according to the square of the slant range; the shorter the slant range, the less total energy that is expended per bit. This implies use of lower altitudes and higher elevation angles.

Communication assumptions and metric computations

The link assumptions used for computing the communications metrics correspond to a typical martian landed element using an omni-directional antenna. If higher gain, actively pointed antennas were used the

Table 3: Communications link assumptions[†]

1.	Omni- directional antenna on the landed element
2.	Omni antenna on the relay spacecraft
3.	500 Kelvin receive system noise temperature
4.	400 MHz communication frequency
5.	3 dB of polarization and feed losses
6.	2. 8 dB of receiver losses
7.	Threshold Eb/ No = 3.2 dB, (K= 7, R= 1/ 2 with (255, 223) R- S Code). Corresponds to BER of 1 x 10e- 6 for non- interleaved codes
8.	Minimum elevation angle of 15°
	∴Data rate of 32 kbps at 1000 km.

data return numbers would shift upwards. However, since comparisons between candidate constellations are relative, the conclusions regarding constellation configurations would not change. This and other link assumptions are listed in Table 3. They yield a base data rate of 32 Kbps at a slant range of 1000 km that can be scaled for different orbit and link geometries using the following calculation sequence to produce the Mean Data Volume/Sol/Watt statistic,

$$\rho_{\max} = (R_m + h)\frac{\sin 6}{\cos \beta}, \tag{5}$$

$$\text{Mean Data Volume/Sol/Watt} = 32\text{Kpbs/watt}\left(\frac{1000\text{ km}}{\rho_{\max}}\right)^2 \left\langle \frac{\text{pass (sec)}}{\text{Sol}} \right\rangle, \tag{6}$$

where $\langle \text{pass(sec)/Sol} \rangle$ represents the average value of the total pass length in a martian day (Sol). This average is computed in several ways for the results presented in this paper. An efficient method developed by Lo[4] applies to non-commensurate circular orbits and uses ergodic theory to arrive at a closed form solution for $\langle \text{pass(sec)/Sol} \rangle$. The second method computes actual sample pass statistics. The constellation evolves forward in time using a simple two-body propagator that includes secular oblateness effects. Landed elements are placed at latitudes between 0° and 90° in 5° increments. The elements viewing geometry of the constellation is sampled, and the pass statistics are computed. This method requires more computations than the ergodic approach, however it applies to all types of satellite orbits. For use in selecting desirable constellation geometries, both approaches yield sufficiently accurate results.

Navigation assumptions and metric computations

Some representative measurement types for the Mars Network include 2-Way range, 1-Way range, and 2-Way differenced range Doppler. The Mars Network will collect these observations and autonomously compute user locations or orbits. Other observable types are being investigated for potential inclusion in the baseline architecture to better support real time positioning, i.e. radio-metric direction finding (RDF). Table 4 identifies the reference assumptions that are used for making comparisons of navigation performance between candidate constellations.

The user position fix uncertainty figure of merit (FOM) is computed according to,

[†] These assumptions are only representative and do not imply the final capabilities or eventual standards that the Mars Network will have.

Table 4: Navigation assumptions‡

1.	2-Way Doppler measurement uncertainty of .5 mm/sec at 60 sec (1σ)
2.	2-Way Range measurement uncertainty of 1 m (1σ)
3.	1-Way Range measurement uncertainty of 1 m (1σ)
4.	User clock fractional frequency stability of 10 E –11 for 60 sec. When estimating positions using 1-Way range it is assumed that the clock errors are estimated simultaneously. The satellite clock is considered to be perfect for analysis purposes (a current specification for this clock is 10 E –14 for 60 secs).
5.	Minimum user terminal elevation angle of 15°
6.	User position uncertainty requirement is 10 m (1σ RSS)
7.	Orbit errors are considered at a level of 2m radial (σ_R), 7 m along track (σ_T), 7 m cross track (σ_N). (These error levels are consistent with the new martian gravity field MGS75B developed from data collected by the Mars Global Surveyor satellite.)
8.	Atmospheric error and other error sources are neglected

$$\mathrm{FOM} = \sqrt{\sigma_{xx}^2 + \sigma_{yy}^2 + \sigma_{zz}^2}\,, \tag{7}$$

where $(\sigma_{xx}, \sigma_{yy}, \sigma_{zz})$ are the epoch state user position uncertainties obtained using simplified covariance analysis tools. In particular, the error sources (data noise and orbit error) are included in the epoch state least squares solution via measurement weights. As an example, slant range errors σ_ρ due to RTN orbit errors are found according to,

$$\sigma_\rho^2 = (\hat{\rho}\cdot\hat{R})^2\sigma_R^2 + (\hat{\rho}\cdot\hat{T})^2\sigma_T^2 + (\hat{\rho}\cdot\hat{N})^2\sigma_N^2\,, \tag{8}$$

where $\hat{\rho}$ is the unit vector along the slant range direction and $(\hat{R},\hat{T},\hat{N})$ are the radial, along track, and crosstrack unit vectors. Note that a more sophisticated orbit error model is currently being implemented that considers gravity field coefficient errors directly rather than indirectly via RTN orbit error levels. Similar to the communication sample statistic computations, the constellation evolves forward in time using a simple two-body propagator that includes secular oblateness effects. Landed elements are placed at latitudes between 0° and 90° in 5° increments. Each element's viewing geometry of the constellation is sampled every minute, and the FOM is computed. When sufficient measurement information has been collected so that a landed user achieves a position fix uncertainty satisfying the threshold value (10 m in this study), the time that it takes to collect this data is recorded. The process repeats with the epoch time reset to the current time. The constellation continues to evolve with the users now at the longitude positions corresponding to the new epoch. The mean response time is computed by averaging over all the collected time values.

CONSTELLATION COMPARISONS

Several constellation scenarios have been analyzed and compared, the candidate constellations parameters are given in Table 2. Because of the competing requirements between navigation and communication, a hybrid constellation concept provides a satisfactory compromise. Figure 5 (top plot) shows the Mean Data Volume/Sol/Watt of transmitted power that can be returned through each constellation from a single surface element. Note that the data return numbers are listed as Mbits/Sol/Watt. If a surface element has 10 watts Effective Isotropic Radiated Power, EIRP, then the data return numbers

‡ As with the communication assumptions, the assumptions listed are only representative and do not imply a final capability of the Mars Network

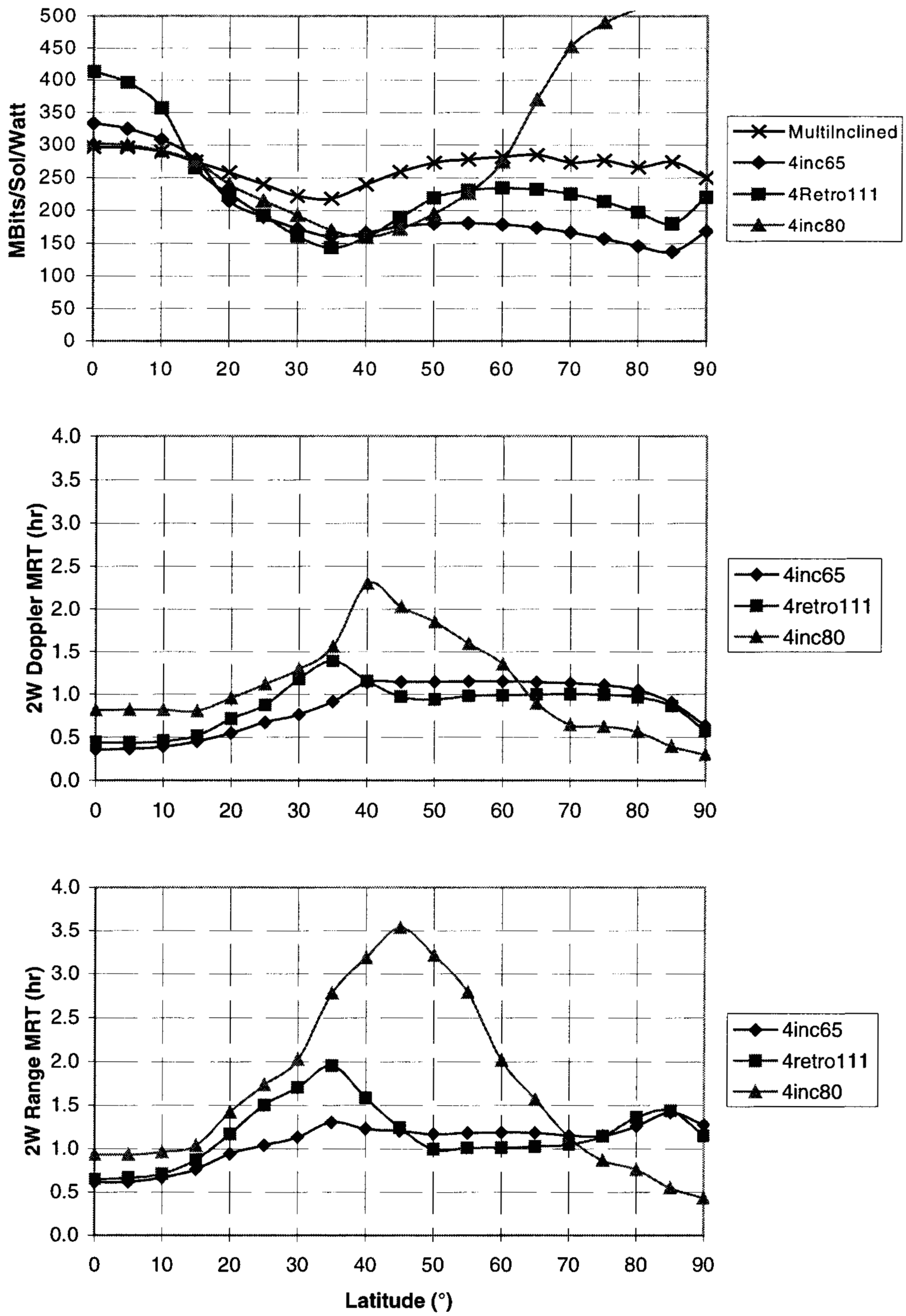


Figure 5: Data return for candidate constellations (top plot), and user position fix mean response time (MRT) to achieve a FOM < 10m uncertainty (middle & bottom plots). The middle plot corresponds to use of 2-Way Doppler measurement data and the bottom plot to use of 2-Way range data.

scale up by a factor of 10. Figure 5 (middle and bottom plots) illustrate the Mean Response Time (MRT) for the candidate constellations using 2-Way Doppler data and 2-Way range data, respectively.

Before discussing specific constellation results, several general comments can be made regarding positioning performance that apply to all the constellations studied. An examination of the range results suggests that range is not as good a data type as Doppler, however this conclusion cannot, in general, be made. Both the range and Doppler performance seen in Figure 5 are impacted by the selected noise values and the simplifications made to model the orbit error. It is anticipated that the actual range noise specifications for the Mars Network will be 10 cm (1σ), an order of magnitude improvement. This combined with improvements to the orbit error modeling may produce a more favorable comparison between the range and the Doppler results. This is an area of current investigation. Although no statistics using 1-Way range have been shown, the MRT figures for this data type are typically the same as the 2-Way range results, assuming the user has a clock as specified in Table 4. Prior analysis has shown that typically a user *cannot* obtain 10 m position fix uncertainties with a clock of 10 E –9 short term stability. Indeed, the actual achieved performance was ~ 100 m position uncertainty. Hence, for mission planning purposes, users that utilize a 1-Way range data type must incorporate a clock with the stability characteristics given Table 4 (or better) in order to achieve a FOM < 10 m.

The 'Multi-Inclined' constellation is designed to maximize data return uniformly across all latitudes. To achieve uniformity of performance many different orbit inclinations were used. However, as discussed previously, the resulting variations in orbit nodal precession rate change the relative orbit plane spacing over time and degrade the pass statistics. There can be periods of weeks where the maximum gap time between successive passes in the mid-latitude region are 10 hours or more. This is an unacceptable constellation configuration and is not considered for further analysis.

The '4inc80' constellation solves the precession problem by placing all of the highly inclined spacecraft in the same altitude and at the same inclination angle. It provides good total data return per sol across all latitudes however there is a bias of coverage near the poles and *not* near the equator. This conflicts with Performance Goal 2 that requires focused support near the equator. Furthermore the low altitude of the upper subconstellation requires the use of a high inclination, recall the condition of Eq. (4). The result is poor performance at the mid-latitudes as compared to the other constellations in this study. The low altitude associated with the 80° inclined spacecraft yields a swath width that covers less surface area than the higher altitude constellations, and produces longer gap times in the mid-latitude locations. The impact of this effect is most notable with the positioning performance. Figure 5 shows that, worst case, the Mean Response Time for both range and Doppler measurement type is nearly twice as long as with the other constellations. The only region where 4inc80 yields superior positioning performance is above 70° latitude.

To improve performance at the mid-latitudes the '4retro111' constellation utilizes a lower inclination (relative to the equator) and a higher altitude than the 4inc80 constellation. Coverage at the poles is also more efficient than with 4inc80. That is, the altitude is raised sufficiently, yet, at the same time, not so high as to introduce large levels of redundant polar coverage. Indeed, the condition of Eq. (4) yields $180 - i + 6 = 92.6°$, and, thus, a 2.6° overlap of neighboring coverage circles (some overlap has been retained for robustness of coverage). This is 3° less than with the 4inc80 constellation. The coverage circle is nearly 50% larger than 4inc80's circle, thus the mid-latitudes receive much more coverage. This is reflected primarily in improvements of the average response time across latitudes below 65° as compared to 4inc80. Overall MRT remains below 1.5 hrs for Doppler data and 2 hrs with range data, and does not exhibit as large of a relative increase at 35° latitude as with 4inc80. Even though the altitude has risen, acceptable data volume numbers are maintained, and it has the best performance near the equator of all constellations considered. Initially, this constellation configuration had been analyzed in its prograde orientation, called 4inc69. However, in this orientation, trajectory analysis of the aerobraking phase for the initial satellite revealed eclipse times that are significantly larger than a maximum allowed value of 2 hours. Changing the inclinations from prograde to retrograde reduced the maximum eclipse times below this threshold. Navigation and communication performance between the two constellations is practically identical, although the pass time statistics differ. The retrograde orientation, typically, has more passes of shorter duration than the prograde case and the maximum gap time is reduced. Because of its superior pass statistics and shorter duration eclipses, the retrograde orientation has been selected over the prograde one.

Table 5: 4retro111 Constellation Buildup Plan

Injection into Trans-Mars Trajectory	*May '03*	*September '05*	*September '07*	*October '09*
Mars Orbit Insertion	*December '03*	*March '06*	*August '08*	*September '10*
Finish Aerobraking	*April '04*	*July '06*	*December '08*	*January '11*
Microsat 0[§]	172°	------		
Microsat 1		172°	------	------
Microsat 2		111°	------	------
Microsat 3			172°	------
Microsat 4			111°	------
Microsat 5				111°
Microsat 6				111°

The '4inc65' constellation is a hybrid constellation consisting of two subconstellations, and the spacecraft altitude has been increased over 4inc80 and 4retro111 altitudes. The navigation performance improvements of this constellation are marginal, and come at the cost of a reduced data volume in the mid to northern latitudes. Furthermore, obtaining a higher altitude requires a larger periapsis raise maneuver after aerobraking is complete. The spacecraft is very weight constrained, and the additional delta-V that this manuever requires adds to an already tight mass budget. Because of these factors selection of this constellation is not warranted. The present conclusion is to baseline the 4retro111 constellation, its performance characteristics meet the desired goals listed in Table 1 better than any of the other constellations examined. The next section of constellation evolution address 4retro111's satisfaction of providing maximum utility during buildup, Performance Goal 5, and redundant coverage in the event of a loss, Performance Goal 6.

MARS NET EVOLUTION

It is necessary to understand how the telecommunications and navigation performance of the 4retro111 constellation evolves as spacecraft are deployed every 2 years. Table 5 lists the deployment strategy starting with the prototype satellite in its final orbit at Mars in 2004, ending with the constellation in its final configuration in 2011. Note how the first near equatorial spacecraft only provides coverage out to ±30° latitude and gap times start to deteriorate rapidly outside 10° latitude. As discussed earlier, elements within 15.6° of the equator receive a pass on every orbit while elements above 15.6° begin to miss passes, and, thus, gap times deteriorate. Nevertheless, this single orbiter provides a significant capability. For users located between ±15° latitude, communication volume is greater than 87 Mbits/Sol/Watt, and positioning to 10 m uncertainty takes under 3 hrs.

On the second launch opportunity two additional comm/nav orbiters are planned with their final orbits attained in 2006. The constellation consists of three elements, two near equatorial at 172° and one inclined at 111°. The inclined spacecraft insures that all locations on Mars get service. The max gap statistic shows a worst case revisit time of 13-14 hours for the higher latitudes. The implication is that users in these regions are now guaranteed a minimum of roughly two passes per sol. The average is 5 passes per sol. The additional equatorial orbiter is phased 180° from the first equatorial orbiter in ascending node. This evenly distributes coverage over the north/south near-equatorial latitudes and provides revisit times of less than 1 hour out to ±10° from the equator, and less than 2 hours out to ±20° from the equator. This installment provides a significant *global* communication and navigation capability. *All* potential users receive a *minimum* of 40 Mbits/Sol/Watt communications volume, and 10 m position accuracies within a MRT of less than 6 hrs.

[§] prototype, not part of the final constellation

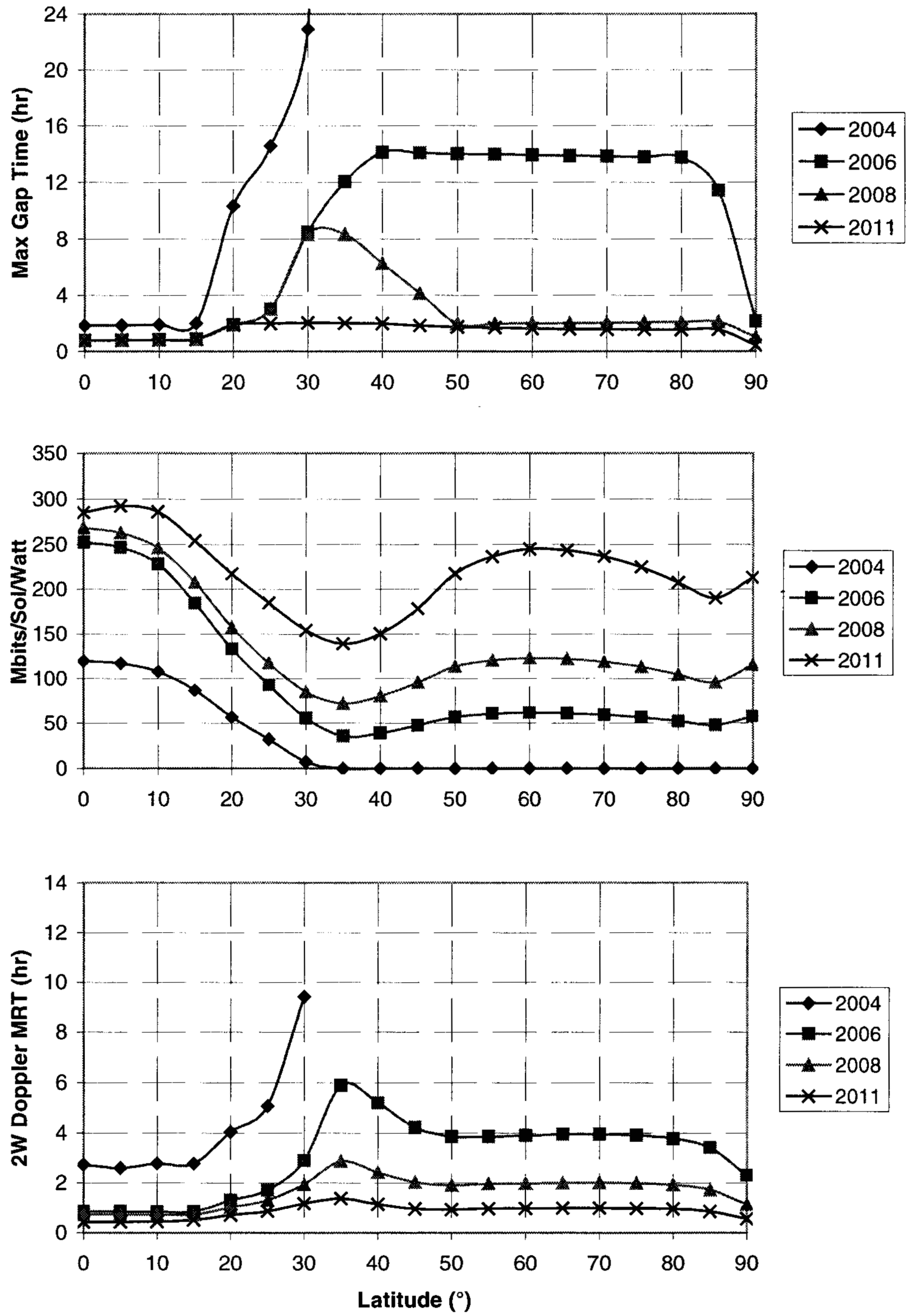


Figure 6: 4retro111 constellation build up performance for the maximum gap time (top), data volume (middle), and mean response time using 2W Doppler data to achieve a FOM < 10m (bottom).

The third deployment opportunity in 2008 sees one more equatorial and one more inclined orbiter deployed. The first equatorial orbiter is assumed to be dead by this time, thus the constellation now consists of two equatorial and two inclined orbiters. The second inclined orbiter dramatically reduces max gap times above 50 degrees latitude. Naturally, the communication and navigation performance is enhanced primarily in the mid and upper latitude regions.

Finally, on the fourth deployment opportunity, adding two more inclined orbiters completes the constellation. At this point the revisit time to any location on Mars is less than 2 hours (on average, with a worst case less than 4 hrs – see Figure 2) and each location is visited on average 15 or more times per sol. In the final configuration, all users receive a *minimum* support of 140 Mbits/Sol/Watt communications volume, and 10 m position accuracies within a MRT of 1.5 hrs.

The performance histories shown in Figure 6 illustrate the ability of constellation to provide capable, although somewhat degraded performance, in the event of a loss of a single spacecraft (Goal 6). For instance, the difference between the 2008 and 2006 configurations is one inclined spacecraft. Hence, the differences in performance between these two configurations are equivalent to the impact of a loss of an inclined spacecraft. Clearly, the 2006 constellation is able to meet the Network's fundamental mission, although its performance is somewhat degraded from that of the 2008 configuration. The buildup history also supports the claim that each successive installment of the 4retro111 constellation provides improving utility (Goal 5). A current area of investigation is aimed at optimizing the constellation parameters and the buildup plan in a systematic way. The continuing effort utilizes a genetic algorithm on a design space that includes altitude, inclination, ascending node phasings, and mean anomaly phasings.

CONCLUSIONS

This study has arrived at a preliminary constellation design that will service the communication and navigation needs of users at Mars while, simultaneously, decreasing the support needed from Earth. The selected constellation, 4retro111, meets many of the stated performance goals, such as global support with a focus at the equator. Its design is robust, in that, a loss of a single satellite yields no catastrophic degradation in global support. Indeed, the complete mission is capable of being conducted (although in a very degraded mode) with only half of the constellation in place. The final configuration represents a significant contribution to the martian communication and navigation infrastructure. It will enhance the current planned missions, and it will enable the development of future, envisioned missions to Mars.

While every effort has been made to do a thorough search for a good design, the approach has nevertheless, been ad hoc. Current efforts are focused on iterating the current design using a systematic search of the reasonable design space for an optimal constellation. Analysis of communication and navigation performance indicates that the maximum gap time is a key characteristic impacting both functions, hence the optimal search is oriented towards minimizing this time. Other areas of continuing work include improvements in the orbit error modeling of the navigation performance tools, and long term perturbation studies.

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